FRm/R41 Suppl

FAO Fisheries Reports No. 41 Suppl. 1 FRm/R41 Suppl. 1 (En)

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Report of the Fourth Session of the

ADVISORY COMMITTEE ON MARINE RESOURCES RESEARCH

Rome, 16 - 21 January 1967

REPORT OF ACMRR WORKING PARTY ON DIRECT AND SPEEDIER ESTIMATION OF FISH ABUNDANCE

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1967

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REPORT OF THE FOURTH SESSION OF THE ADVISORY COMMITTEE ON MARINE RESOURCES RESEARCH

16 - 21 January 1967

REPORT OF ACMRR WORKING PARTY ON DIRECT AND SPEEDIER ESTIMATION OF FISH ABUNDANCE

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, May 1967

PREPARATION OF THIS PAPER

This is an edited version of the ACMRR/3/WP.18 as amended by correspondence and later at the informal session of the Working Party in Copenhagen attended by some of its members. The present revised version was considered and approved by the 4th Session of the Committee.

Distribution :

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"Current Bibliography" entry :

ACMRR(FAO). Fourth Session. 12-5M039
Rome, 16-21 January 1967 (1967)
FAO Fish.Rep., (41)Suppl.1:31 p.
Report of the fourth session of the Advisory Committee on Marine Resources Research, 16-21 January 1967. Report of ACMRR working party on direct and speedier estimation of fish abundance.

Fish detection. Acoustic methods. Physics of acoustics. Identification of records. Echo counting. Optical methods.
Co 12-1M056. Do 10-114me, 10-099.1me

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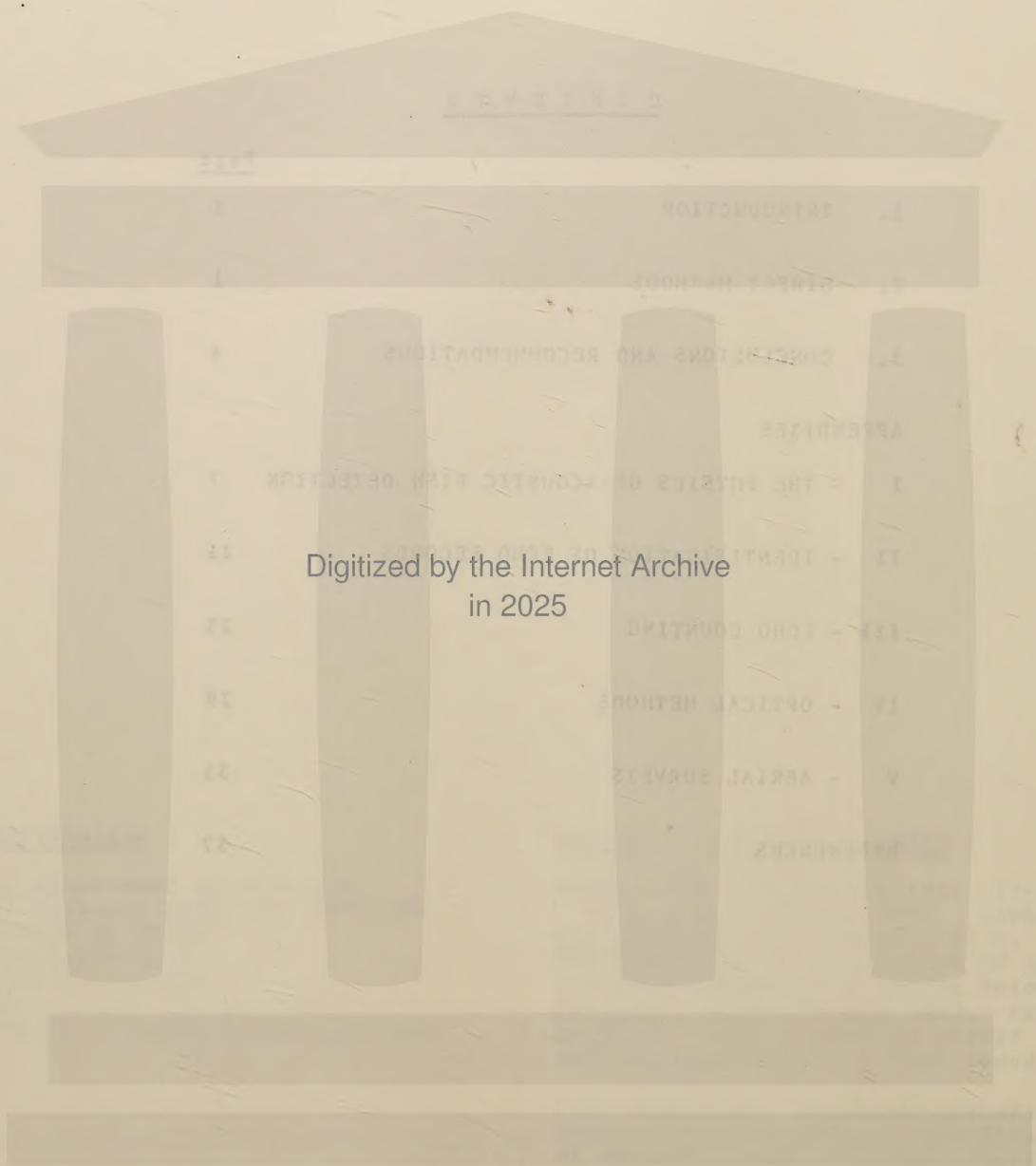

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1. INTRODUCTION

With reference to its programme of work in the field of marine resources appraisal, FAO has become increasingly aware of the important development, in recent years, of new methods of estimating the abundance of fish stocks. Following a general discussion of this problem at its second session in Rome in February 1964, the FAO Advisory Committee on Marine Resources Research (ACMRR) established a Working Party of experts to review recent work "in the rapidly developing field of the direct and speedier estimation of fish abundance, by the use of echo-sounders and by other methods" (ACMRR, Report of Second Session: FAO Fisheries Reports No. 20, Recommendation 12).

The Working Party, consisting of Mr. B.B. Parrish (Convener), Dr. D.N. Cushing, and Mr. L.S. Midttun, after conducting preparatory work by correspondence, met in Rome from 25th - 28th February 1965 to prepare a Report which was submitted to the 3rd Session of ACMRR in Rome, March 1965. At their session they were assisted by Dr. G.L. Kesteven (a member of ACMRR), Mr. V. Valdez (FAO Consultant), Mr. E.F. AkyÜz and Mr. L.K. Boerema (staff members of the then Biology Branch, Fisheries Division, FAO), and Dr. M. Ruivo (Secretary to ACMRR). After that session, the membership of the Working Party was broadened (see ACMRR/3/Rec. 9) to include Prof. Y. Hiyama, Dr. G.L. Kesteven, Mr. M.N. Scherbino and Dr. R. Whitney. The enlarged Working Party continued its activity during 1965 and 1966 by correspondence. Some of its members (Mr. B.B. Parrish, Dr. D.N. Cushing and Mr. L.S. Midttun), who were attending the Statutory Meeting of ICES in Copenhagen (Sept. 29 - Oct. 1, 1966) met to discuss outstanding points on the question of echo-sounding, after which the Convener submitted the present revised version of the Report for consideration by the ACMRR.

The Working Party took as its main task an assessment of the potentialities, limitations and current state of development and applications of methods of estimating the relative and/or absolute abundance of marine fish stocks which might be used together with - or instead of - the "traditional" ones of sampling by fishing gear and of marking. While the "traditional" methods have been - and are likely to continue to be - important for estimating the abundance of exploited fish stocks in areas where the organised collection of fishery statistics, catch sampling and related scientific investigations are carried out, they are subject to limitations and shortcomings when used by themselves, especially for estimating absolute abundance. Furthermore, the traditional methods are inadequate and time consuming for obtaining initial estimates of abundance in exploration of unexploited resources. In its appraisal, the Working Party considered fully the use of direct methods, using acoustic or optical fish selection methods, the use of which has grown in recent years.

Indirect methods, based on the estimation of the production of spawning products were also briefly considered as a support to echo-surveys in unexplored areas. Such surveys require good estimates of fecundity and sex ratio and hence adequate fish catching for sampling purposes, and the proper identification of egg and larvae subsequently. Both egg and larvae surveys can be used to provide estimates of absolute abundance but with the latter substantial underestimates are likely to be obtained, unless the mortality occurring up to the time of sampling can be taken into account.

2. DIRECT METHODS

2.1 Acoustic Methods of Fish Detection

2.1.1 Historical Development

Acoustic methods of abundance estimation can be used in two ways: firstly, for exploited populations, as a powerful extension of fleet and research vessel sampling, and secondly, for the exploration of unfished populations. Echo-sounders and sonars are used for both purposes. The echo-sounder gives detailed information on numbers of individual fish targets, or school targets, in a vertical trans-

mission, while sonar gives the number of schools in the search field in a nearly horizontal transmission. The physical principles of acoustic fish detection are discussed fully in Appendix I. The first acoustic technique to be developed was echo-sounding which was introduced towards the end of the 19th Century as a navigational tool for determining water depth, but the ultrasonic oscillator, from which the modern developments in echo-sounding stem, was not introduced until the first World War. Its potentialities as a fish detection device were first recognized in the 1930's by Anon (1934) and Sund (1935) in Norway, and Balls (1945) in England. These early results were subsequently confirmed, and there followed, especially after the second World War, intensive developments by echo-sounder manufacturers, fishermen, and fishery scientists towards improving the equipment for fish detection, for commercial fishery and for research purposes. The introduction of sonar for fish detection also took place in the early postwar years, particularly in Norway (Gerhardsen (1946); Devold (1950)). These early developments and the state reached in their application by the 1950's are reviewed in a "Report on Echo-Sounding and ASDIC for Fishing Purposes" prepared by a Working Party set up by ICES in 1954 (Hodgson and Fridriksson (1955)). For the purposes of this report echo-sounders are considered to transmit vertically and sonar at an angle to the vertical.

The first steps in the direction of abundance estimation were taken with the introduction of systematic echo surveys over the areas occupied by exploited pelagic fish concentrations and the correlation of the centres of echo density with the distribution of commercial catches. Early published examples of such echo-sounding surveys and their use for such purposes are given by Runnstrom (1941) for the spawning concentrations of Atlanto-Scandian herring off the west coast of Norway; Cushing (1952) for herring in the central and southern North Sea; Krefft and Schuler (1951) and Craig and Parrish (1952) for herring in the northern North Sea, Richardson (1950, 1951) for the sprat, and Tester (1943) and Hourston (1953) for the Pacific Herring. The use of sonar surveys has been developed by Devold (1951) for Atlanto-Scandian herring. These investigations demonstrated clearly the potentialities of acoustic equipment as a quantitative tool, at least for pelagic stocks, and stimulated further detailed studies of the technical and quantitative elements of the echo survey method (Scherbino and Truskanov (1966); Dragesund and Olsen (1965)) including its application to estimating abundance of demersal fish stocks (Richardson et al. (1959)). Its use for this purpose, however, poses more difficulties than in studies of pelagic stocks, but they are being overcome with the use of narrow beam, high resolution,equipment.

2.1.2 Principal Problems

There are three principal problems in using acoustic equipment to estimate fish abundance; first, the identification of targets; second, the counting of targets; and third, the combination of and solutions to the first and second problems in a survey technique.

a) Identification of targets

Targets cannot yet be identified acoustically. It is possible, however, to make a rough estimate of the sizes of targets by various methods: for example, from their target strengths. But fish of the same target strength in the same area may be of different species. It is possible that they can be distinguished locally by their shoal formation, as recorded by echo-sounders, and/or by their response to particular environmental conditions. Where this is not possible, identification by direct underwater observation is necessary. The problem of identification of targets is dealt with in more detail in Appendix II.

b) The counting of targets

The first requirement for any form of counting, even the simplest based on the presence or absence of targets, is that the acoustic system be calibrated - calibration procedures are described in Horton (1957). Further, any counting system presupposes that the targets are larger than a given size. Consequently, the maximum range at which the smallest target can be detected is the range of the system, and this defines its sampling volume.

When a bottom survey is considered, the volume sampled by one transmission in the 1 or 2 meters above the sea-bed is limited to a region very close to the axis of transmission (see Appendix I). This volume can be enlarged by using a sector scanner, which scans in bearing, with a fixed, multichannel transducer.

There are three methods of counting, increasing in degree of sophistication as follows :

1) by recording the presence or absence of fish in a single transmission. This is the method commonly used on echo survey, but, to be sure that absence of signal means absence of targets, the system must be calibrated and operated within the maximum range of the smallest target;

2) by counting the number of individual fish where these are resolved by the equipment or, where this is not so, the estimation of the number of individuals in a multiple echo. The former can be done under the best conditions by counting the individual traces on a paper record (Midttun, Saetersdal and Vestnes (1957)), but for the latter, as for example when signals are received from fish in shoals, some physical assumptions have to be made about the way in which the energy is reflected. These are discussed in Appendix III where some empirical rules for treating multiple targets are given. The objective of any counting system should be to count individuals. This can be achieved by increasing transmission frequency and, for smaller fish, by shortening pulse length;

3) by counting the targets in a scanned beam of a sector scanner (Voglis and Cook (1966); Cushing and Harden Jones (1966)).

c) Survey techniques

The details of a survey plan, including those of the operational grid in surveying an area by echo-sounder or sonar, should be decided upon with respect to local conditions.

Horizontal transmissions are always modified by thermal layers in the water, which affect the effective range of sonar, but, given the required hydrographic conditions, this can be determined (see Appendix I). Under favourable conditions, a sonar can search a band of water as much as 5 km wide. The echo-sounder on the other hand searches a much smaller volume of water, the band searched often being no more than 30 meters wide. The survey plan must take these facts into account when a grid is drawn up, as well as any available information on fish distribution. When a survey of demersal fish is attempted, it must be remembered that the effective volume is limited to a region near to the axis of transmission.

Any survey technique should employ methods of fish capture either for identification purposes or to establish the relation between catch per unit effort and signals received from fish targets. Each should be expressed as per unit volume sampled by the fishing gear and by the acoustic apparatus. Then the variance of the

estimate of abundance in the whole survey area is a function of the number of unit volumes searched and the average number of fish per unit volume. Navigational aids are needed for the good fixing of positions in any survey.

2.1.3 Present Status of Methods

The present status of the methods may be summarized as follows: echo surveys for both pelagic and demersal fish have been successfully used in many countries, based on a presence or absence technique to estimate relative abundance. More sophisticated counting surveys, of individual and/or multiple targets, aimed at estimating absolute abundance using calibrated equipment have been made in recent years (see Appendix III). It is likely that the future use of high resolution sector scanners and other equipment will make echo surveys for abundance more effective.

2.2 Direct Under-Water Optical Methods

Except in the limited situations of sedentary, benthic organisms the main use of direct under-water optical methods (including direct visual observations by free-swimming divers or from under-water vehicles, photography and television) for abundance estimation has been, and is likely to continue to be, in supplying "spot" information on the identity and density (as numbers per unit volume) of organisms in concentration recorded by acoustic methods. Still cameras, with electronic flash fitted with a known target for calibration purposes, are likely to be the most useful equipment for this purpose. The development of stereo-cameras for these uses would assist in identifications and counting in many instances. Cine-cameras and under-water television can be used in some situations, and divers, with or without cameras, can operate in shallow water. However, there is considerable hope that manned under-water vehicles combining acoustic and optical methods will be used for these purposes in a much wider range of situations in the future. These methods are discussed more fully in Appendix IV.

2.3 Aerial Surveys

In some special situations where surface schooling fish occur, it is possible from aerial surveys to estimate reliably and quickly the abundance of a stock in a large well-defined area. More often, however, the main value of aerial survey lies in its contribution to surface vessel operations. In some cases it has been used in exploratory work to ascertain the main features of an area, including determination of the presence of surface schooling fish. In other cases it has been used to guide and assist surface survey operations. First, for determination of an area occupied by surface schooling fish, thus helping to reduce the use of vessel time in areas not occupied by the fish. Second, to provide a synoptic picture of the distribution of fish schools and oceanic features. Third, to guide the surface craft to centres of fish concentration. In the main these contributions serve to increase the efficiency and reduce the relative costs of surface operations. But in some circumstances, aerial survey also makes its own contribution of data from which estimates of relative abundance can be made. A more detailed discussion of aerial surveying methods is given in Appendix V.

3. CONCLUSIONS AND RECOMMENDATIONS

Of the direct and indirect methods of estimating relative or absolute abundance of fish, considered by the Working Party, acoustic fish detection techniques have the greatest potentialities and the widest application both in exploratory resource measurement investigations, and in detailed population studies of exploited stocks.

Existing commercial acoustic detection equipment, when calibrated, can be used to give estimates of relative abundance and, when combined with other methods of measuring density (e.g. photography), also rough estimates of absolute abundance. Such methods can be applied equally in surveys in unexplored areas and in fleet or research vessel sampling of exploited stocks.

For estimating absolute abundance directly, however, more specialized equipment with high resolution, in conjunction with counting systems is needed. Such equipment, including high frequency, calibrated, narrow beam echo-sounders, sector scanners and FM scanners, are under development and coming into use in some countries. Because of their great potentialities for abundance estimation the Working Party recommends that their development and subsequent operational trial in such work, in as wide a range of situations as possible, be encouraged As far as possible, opportunities that might be offered for this purpose by FAO's field programs should be followed up.

In association with the use of such equipment for abundance estimation, further research is needed, especially on :

a) the target strengths of individuals and shoals of fish (in all directional aspects) of different sizes and species;

b) acoustic methods of determining the size of fish, frequency ratios and methods based on air bladder resonance;

c) the discrimination of fish targets from bottom reverberation;

d) the identification by photographic methods of fish detected by acoustic equipment.

With the rapid growth in the use of acoustic fish detection equipment in fisheries research, the need arises for fishery scientists concerned with fish stock evaluation problems to be better informed of their principles, characteristics and use. The Working Party therefore recommends that FAO takes steps to promote a better understanding of these techniques and their application, by convening a symposium and arranging seminars on "The direct estimation of abundance of fish by acoustic methods", by engaging consultants to prepare and to publish a training manual on the physical principles of acoustic equipment and their application in fisheries work, and by holding training courses for fishery scientists, analogous to the ICES and FAO courses on population analysis.

In the application of the echo-survey method, as with all sampling methods, problems arise concerning the design of the survey, the extent, intensity and efficiency of which govern its cost and the accuracy of abundance estimates derived from it. No theoretical statistical treatment of the design of such surveys is currently available and the Working Party therefore further recommends that a study be made of their statistical basis, with special reference to design factors and the estimation of the variance of estimates.

Egg and larvae surveys are of value in exploratory work, in support of echo-survey to chart the centres of density of spawning fish. If good estimates of fecundity and sex ratio are available from catch sampling, estimates of absolute abundance of spawning fish can be obtained, especially from well-planned egg surveys.

APPENDIX I

THE PHYSICS OF ACOUSTIC FISH DETECTION

I BASIC THEORY

The physical principles, concepts and relationships involved in acoustic fish detection techniques are summarized below. A more comprehensive treatment of some of these subjects is given in the publication "The Physics of Sound in the Sea" (Lyman Spitzer jr. (ed) 1946) and by Horton (1959).

1 Sound Transmission

1.1 Sound pressure, p. Sound waves are described in terms of pressure disturbance, and normally as "sound pressure", which is the average rms value of the instantaneous sound pressure or 0.7 times the pressure amplitude averaged over a few cycles. Sound pressure is given in dynes per sq.cm.

1.2 Sound field intensity, I, is the average power carried by a sound wave per unit cross section of a wave front, and is measured in watts per sq.cm.

Sound pressure, p, and intensity, I, are related as follows :

$$I = 10^{-7} \frac{p^2}{\rho c} \qquad (1)$$

where ρ is density in gm/cm^3 and c is the sound velocity in cm/sec.

It is convenient to use the logarithmic decibel scale and sound field intensity in decibels is reported as sound level, L, above a standard value, corresponding to a sound pressure of 1 $dyne/cm^2$.

Therefore $L = 20 \log p \qquad (2)$

1.3 Source level, S, is a measure of the power output of a sound source on a decibel scale, or the sound level at a distance of 1 yard from the source, normally reported at the acoustic axis. If the power output per unit solid angle is called F, then, in the case of a point source and a homogeneous non-dissipating medium

$$I = \frac{F}{d^2} \qquad (3)$$

where d is the distance from the source.

In terms of decibels :

$$\begin{aligned} 10 \log I &= 10 \log F - 20 \log d \\ L &= S - 20 \log d \end{aligned} \qquad (4)$$

Sound transmitted from a transducer needs a more detailed specification. The distribution of sound energy emitted in different directions can be described by a pattern function $b(\theta,\phi)$, dependent on the nature of the transducer, where (θ,ϕ) denotes a direction in space.

When F max. is taken as $F(0,0)$, called the acoustic axis of a transducer, b is defined by

$$F(\theta,\phi) = F(0,0),b(\theta,\phi)$$

The function b so defined is a quantity between 0 and 1.

The sound intensity at a point (d,θ,ϕ) is thus

$$I(d,\theta,\phi) = \frac{F(0,0) \cdot b(\theta,\phi)}{d^2}$$

or in terms of decibels

$$L_{(d,\theta,\phi)} = S + 10 \log b_{(\theta,\phi)} - 20 \log d \qquad (5)$$

again given a homogeneous, non-dissipating medium. Sea water is not an ideal medium; therefore another term must be added to equation (5), namely, transmission anomaly.

1.4 Transmission anomaly, A, is a quantity describing the drop of sound level during transmission through the water other than geometric spreading as described by the inverse square law. Thus,

$$L_{(d,\theta,\phi)} = S + 10 \log b_{(\theta,\phi)} - 20 \log d - A \qquad (6)$$

The transmission anomaly is caused by two groups of factors. The first one is called attenuation and includes absorption and scattering. The second is called the spreading anomaly and includes refraction but also reflection from the boundary surfaces. The spreading anomaly must be taken into consideration when using sonar, and is dealt with in Section II below. In echo sounding the spreading anomaly can be disregarded and the transmission anomaly is caused by attenuation only :

$$A = \frac{ad}{1000} \qquad (7)$$

where d is the distance in yards and a is the attenuation coefficient, measured in decibels per kiloyard, which increases with increasing transmission frequency. Due particularly to changing scattering conditions in the sea, the attenuation is also changing by time and location, but some average values are given in Table I below.

Table I - Attenuation coefficient in the sea (according to Lyman Spitzer jr. (ed) 1946)

Frequency kc/s	30	50	100	500
a db/kiloyard	6	13	35	150

Often the drop in sound level caused by both geometric spreading and transmission anomaly is called the transmission loss (or the propagation loss) which is therefore given by

$$H = A + 20 \log d \qquad (8)$$

2 Sound Reflection

When sound is reflected by a target, the intensity of the reflected sound I_r measured at a distance d' is

$$I_r = k\frac{I_o}{d'^2} \qquad (9)$$

where I_o is the intensity of the incident sound at the target and k is a constant, dependent on the nature of the target. The same formula, expressed in decibels is

$$10 \log I_r = 10 \log k + 10 \log I_o - 20 \log d' \qquad (10)$$

Strictly, this formula is valid only in a homogeneous, non-dissipating medium, and when applied to the sea, the term of the geometric spreading must be replaced by the term transmission loss H.

$$10 \log I_r = 10 \log k + 10 \log I_o - H \qquad (11)$$

In echo-sounding and sonar, the reflected sound is received at the source: therefore d = d'. The level of the incident sound at the target can be expressed by the formula (6), combined with (8), thus giving

$$10 \log I_o = L_{(r,\theta,\phi)} = S + 10 \log b_{(\theta,\phi)} - H \qquad (12)$$

The level of the reflected sound, called <u>echo level</u>, E, is therefore :

$$E = 10 \log I_r = 10 \log k + S + 10 \log b_{(\theta,\phi)} - 2H \qquad (13)$$

Since this echo is measured through a receiver with a directivity pattern $b'(\theta,\phi)$ defined by $I_r(\theta,\phi) = I_r(0,0)b'(\theta,\phi)$, the echo from the direction (θ,ϕ) will be

$$E_{(\theta,\phi)} = 10 \log k + S + 10 \log b_{(\theta,\phi)} + 10 \log b'_{(\theta,\phi)} - 2H \qquad (14)$$

In echo-sounding and sonar the same oscillator is normally used both for transmitting and receiving, so that if its transmitting and receiving properties are the same one will have

$$E_{(\theta,\phi)} = 10 \log k + S + 20 \log b_{(\theta,\phi)} - 2H \qquad (15)$$

For echoes on the acoustic axis this formula is reduced to

$$E_{(0,0)} = 10 \log k + S - 2H \qquad (16)$$

3 <u>Target Strength</u> (T)

The quantity 10 log k is called the target strength, T, and is dependent on the nature of the target. Target strength can also be expressed by a quantity σ, called effective target area or <u>scattering cross section</u>, and defined as follows :

If the echo received was reflected by a total reflecting target with uniform spherical reflectivity pattern, the area of this target normal to the incident sound would be equal to σ. T and σ are related by the expression

$$T = 10 \log \frac{\sigma}{4\pi}, \text{ since } \frac{\sigma}{4\pi} = k \qquad (17)$$

3.1 <u>For single targets.</u> The target strength of a single target is dependent on several factors, viz.:

a) The acoustic property of the target in relation to water, expressed by the <u>index of reflection</u>, μ

$$\mu = \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \qquad (18)$$

where ρ is the density, c is velocity of sound and the indices 1 and 2 indicate water and target.

b) The size of the target in relation to the wavelength of sound. If size is described by a parameter, l, and the wavelength is λ, one distinguishes between three magnitudes of this relation,

i) where $\lambda << 1$ the target strength can be found by using laws of geometric optics.

ii) where $\lambda >> 1$ (the so-called Rayleigh scattering zone) the scattering cross section can be shown to vary inversely with the fourth power of the wavelength.

iii) In the intermediate zone where wavelength and target size are similar, the target strength is very dependent on the size, geometry and orientation of the target.

The pulse length, τ, comes into consideration only when the length of the pulse in water (τc) is small compared to the target size.

So far as fish are concerned, although some direct measurements of target strength have been made, considerably more data are needed in order to establish a satisfactory law for sound reflection by fish of different species and size. From those measurements already made (Midttun and Hoff 1962, Cushing 1965), some conclusions can be drawn as follows :

(a) There is a clear relationship between the size of the fish and its maximum target strength. In the transmission frequency range 30-40 kc/s, target strength is about -35 db for fish of 20 cm and increases to about -18 db for fish of 70 cm.

(b) The target strength is greatly affected by the aspect of the fish relative to the acoustic axis.

(c) The airbladder plays an important role in determining the reflection pattern, indicating that even the geometry of the bladder must be taken into consideration.

3.2 Multiple targets. Given two targets at distances d_1 and d_2 from the transducer, they will be recorded as single echoes if $d_1 - d_2 > \frac{1}{2}\tau c$.

In the case where d_1 and $d_2 < \frac{1}{2}\tau c$ their individual echoes cannot be distinguished and the received signal is a multiple echo.

Considerable work has been done in the field of multiple echo theory when the scatterers are small airbubbles produced in ship wakes. From this theory, based upon some basic assumptions, it is possible to compute the density of bubbles up to a certain limit, provided that the scattering and absorption properties of a single bubble are known. For low bubble densitites the scattered intensity of a bubble screen can be regarded as proportional to the number of scatterers.

How far it is possible to apply this theory to the number of fish in a shoal and the multiple target strength is not fully known. However, some workers have used a relationship in which the echo intensity is directly proportional to the number of fish (see Appendix III). This is likely to give an under-estimate of the number of fish for a given echo intensity for densely shoaling species.

II METHODS OF SONIC FISH DETECTION

For fish detection and abundance estimation two types of sonic instruments are now in use. They are :

1. Echo sounder
2. Sonar

1 Echo Sounding

Echo sounders have been used for the purpose of abundance estimation both on dispersed concentrations by adopting the so-called "counting method" and on denser concentrations such as shoals of fish by measuring the size and

density of the shoals. A special type of concentration formed by layers of fish fry has also been measured by the echo sounding technique. These methods are discussed below.

1.1 Echo counting. This subject will be discussed separately in Appendix III. Here it will be introduced only from a theoretical point of view.

It is necessary first to define a number of terms. These are as follows :

1) The incoming information from one target in one transmission is an echo: many targets in one transmission form together a signal composed of many single echoes or multiple echoes.

2) A trace is one or more echoes given by the same target during several transmissions.

If traces caused by single fishes can be distinguished the number of traces per unit distance steamed provides an estimate of abundance if the abeam sampling cross section of the echo sounder is known.

The sampling cross section (abeam)

In equation (15) the echo level is given by :

$$E_{(\theta,\phi)} = T + S + 20 \log b_{(\theta,\phi)} - 2H$$

In echo sounding, the transmission loss H can be taken as

$H = \frac{ad}{1000} + 20 \log d$ since the transmission anomaly, A, is an effect of attenuation only.

If the lowest echo level at which a fish is recorded is called the MRS (minimum recordable signal), and for reason of simplificiation transmission loss is taken as being due to geometrical spreading only, ignoring attenuation (H = 20 log d), equation (15) can be rewritten

$$MRS = T + S + 20 \log b_{(\theta,\phi)} - 40 \log d \qquad (19)$$

When MRS is conventionally determined and S is known (source level at axis) then the sampling cross section for a certain target strength, T, can be found from the above equation, provided the pattern function $b(\theta,\phi)$ is known. (Fig. 2)

Estimation of average target strength within the beam

When an echo is received, the location of the target within the beam is not known. It could be reflected from a target with low target strength but close to the acoustic axis, or it could be from a target with large target strength located correspondingly far from the axis.

Some more information is obtained when traces are analysed since both numbers of echoes in one trace and the average echo strength for the whole trace (trace strength) can then be measured. If for example the number of echoes in one trace could be taken as a measure of the average θ during the passage, then the trace strength could be used for target strength computation. In practical work some averaging is necessary and the easiest way is to regard all signals as being recorded within the h half value angle, θ_s. Provided the oscillator has been constructed with θ_s close to the first minimum (i.e. with a steep cut off of the beam) a fairly good estimation of the average target strength can be made.

It has been mentioned previously that a fairly good relation exists between fish size and their maximum target strengths. But the actual target strength of a fish varies according to its aspect within the beam. If we can regard all fishes as being in a horizontal position, the

location and aspect of a fish in the beam can be described by the two angles θ and ϕ together with a third ψ, between a certain reference direction (i.e.) the course) and the long axis of the fish taken positive from tail to head. As a basis for averaging therefore a detailed knowledge of the dorsal reflectivity pattern of fish as a function of θ is necessary. The variation in this is least with a narrow beam, i.e. $\theta_{max.}$ (at MRS) is a small angle, say 5^{o}. However, in using such a narrow beam in practice, the transducer should be stabilized.

Fish near the bottom

For an echo from a fish near the sea bed in a vertically directed beam to be distinguished from the sea bed echo, its distance from the sea bed, h, might satisfy the following conditions :

$$h > \frac{1}{\cos \theta} \left(\tfrac{1}{2} c\tau + d \left(\frac{1}{\cos \theta} - 1\right)\right) \qquad (20)$$

For an echo on the acoustic axis ($\theta = 0$) the equation is reduced to

$$h > \tfrac{1}{2} c\tau \qquad (21)$$

A small h is obtained when the pulse length is small. Very high resolutions can be obtained by using high frequencies. Another possibility is to use frequency modulation. Another possible approach to the problem of recording fish near the bottom is the use of a narrow, but tilted, beam: the best results are probably obtained by using a sector scanner.

1.2 Measurement of shoals. The width of a shoal can be measured by an echo sounder when the ship is passing over it. The measurement of its vertical extent is more difficult, but provided the shoal is not too dense, it can be done by a narrow beam sounder. The best estimate will be given by a sector scanner.

The density of the shoal is the parameter which is the most difficult one to measure. Possible methods of estimation are :

i) the use of a very narrow beam ("acoustic string") by which the shoal is split into single targets. This method gives also the possibility to measure the target strength of single fishes, and hence their size distribution.

ii) estimation of the number of scatterers by measurement of their multiple echo. As already mentioned above, such computation would require knowledge of the target strength of each scatterer which could be averaged since all fish in a shoal are of the same species and nearly of the same size. Further, the relation between the multiple target strength and number of scatterer must be known. The basic theory has not yet been derived. An empirical relationship for Atlanto-Scandian herring has been established by Truskanov and Scherbino (1964).

iii) non-acoustic methods, i.e. photography, television, and fish capture.

2 Sonar

The application of sonar is limited to the study of pelagic fish such as herring often found in well defined shoals distributed over a rather large area and with a relatively low number of shoals per unit area.

If the sound rays can be regarded as straightlined, the depth, h, of the layer searched depends on the directivity pattern, b, of the transducer and the range, d.

2.1 The directivity pattern $b(\theta,\phi)$ for a transducer is an empirical function which has to be found by testing each particular transducer. But generally the pattern function can be expressed by the equation of diffraction

$$b = \frac{\sin^2\beta}{\beta^2} \quad \text{where } \beta = \frac{\pi a}{\lambda} \sin\theta \tag{22}$$

(a is the width of the transducer, λ the wavelength and θ is the angle from the acoustic axis).

2.2 Beam angle. In practical echo ranging procedure the so-called half value angle, θ_s, has been adopted as the limiting beam angle. θ_s is the angle at which the intensity has dropped to half of the axis' value, i.e.

$$b = \tfrac{1}{2}, \quad \text{and } 10 \log b = -3 \text{ db}$$

As a good approximation for a square transducer,

$$\theta_s = \pm 25 \frac{\lambda}{a} \tag{23}$$

the depth, h, is then

$$h = d \sin\theta_s \tag{24}$$

2.3 The range, d, can be found from equation (15), by introducing as echo level E the minimum recordable signal MRS, depending on the noise level. Thus (in decibel units)

$$MRS = T + S - 6 - 2H \tag{25}$$

Since $H = 20 \log d + A$ and on the assumption of straightlined propagation,

$$A = \frac{ad}{1000},$$

one has $$MRS = T + S - 6 - 40 \log d - \frac{2ad}{1000} \tag{26}$$

Therefore in order to find the maximum range, d, within the beam angle, the source level, S, and the target strength, T, of the shoal must also be known.

2.4 Layer effect. The above theory considers straightlined propagation of the sound, an assumption which is valid only if the velocity of sound can be regarded as constant. In the sea this is not the case since sound velocity varies with temperature t°, salinity $S(\%_o)$, and pressure p. Approximately,

$$c = 1400 + 4.9t^\circ - 0.044t^{\circ 2} + (1.32 - \frac{t^\circ}{100})S\%_o + 0.018(1 - \frac{t^\circ}{100})p \tag{27}$$

It is seen that temperature has the greatest influence on the change in sound velocity. The temperature variation in the sea is often rather large vertically, and so is therefore also the sound velocity, resulting in a deflection of the sound beams. Under such conditions the transmission anomaly, A, is highly variable. In and below a temperature discontinuity the transmission anomaly, A, will be large, resulting in poor sound propagation conditions. This is called the layer effect. In Figure 1 A-D are shown four typical transmission patterns constructed from measured conditions in a locality off the west coast of Norway. It is possible to predict values for A when the vertical distribution of sound velocity is known.

It is evident therefore that an effective sonar survey can only be undertaken when

(1) The sonar conditions are known, i.e. temperature and in some areas also salinity measurements must be undertaken in order to be able to predict values of A.

(2) In order to predict the range, d, it is further necessary to know :

i) The target strength, T, of the shoal
ii) The noise level, in order to fix the value of MRS
iii) The source level, S, of the sonar must be known.

The next steps in estimating fish abundance are measurements of shoal size and density. Those parameters cannot be measured by most sonar gears.

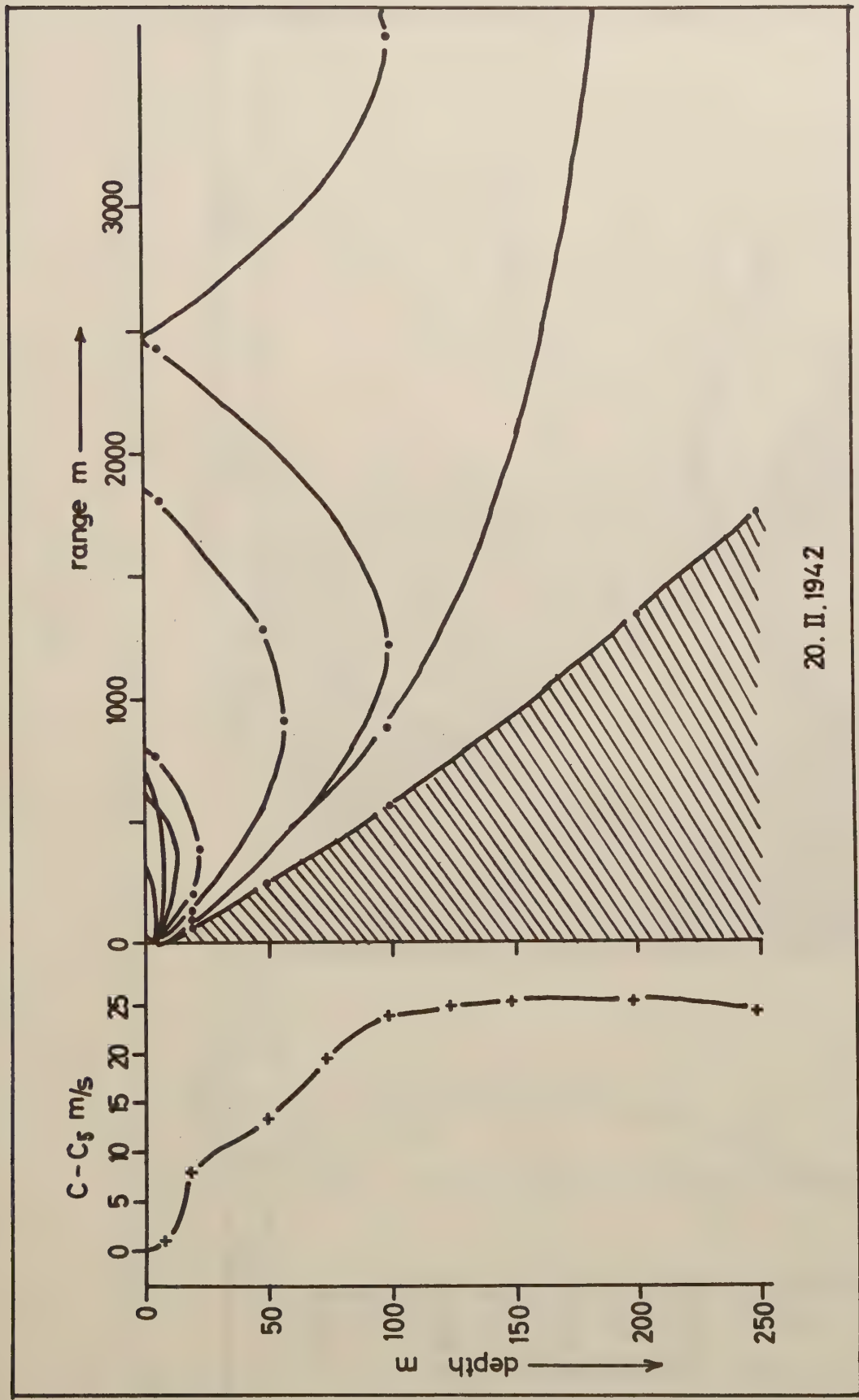
Figures

Figure 1 : A - D. Four typical sound ray transmission patterns computed from measurements of sound velocity in a locality off the Norwegian coast. Half value angle $\theta_s = \pm 12{,}5^{\circ}$. The shadow zone is shown hatched. C_5 is the sound velocity (m/s) at 5 m.

Figure 2 : The sampling cross section at different values of target strength, T. Half value angle θ_s is indicated. As a basis for computation :

Frequency	30 kc/s
Transducer width	12 cm
Source level	110 db
MRS	-30 db

Transmission anomaly neglected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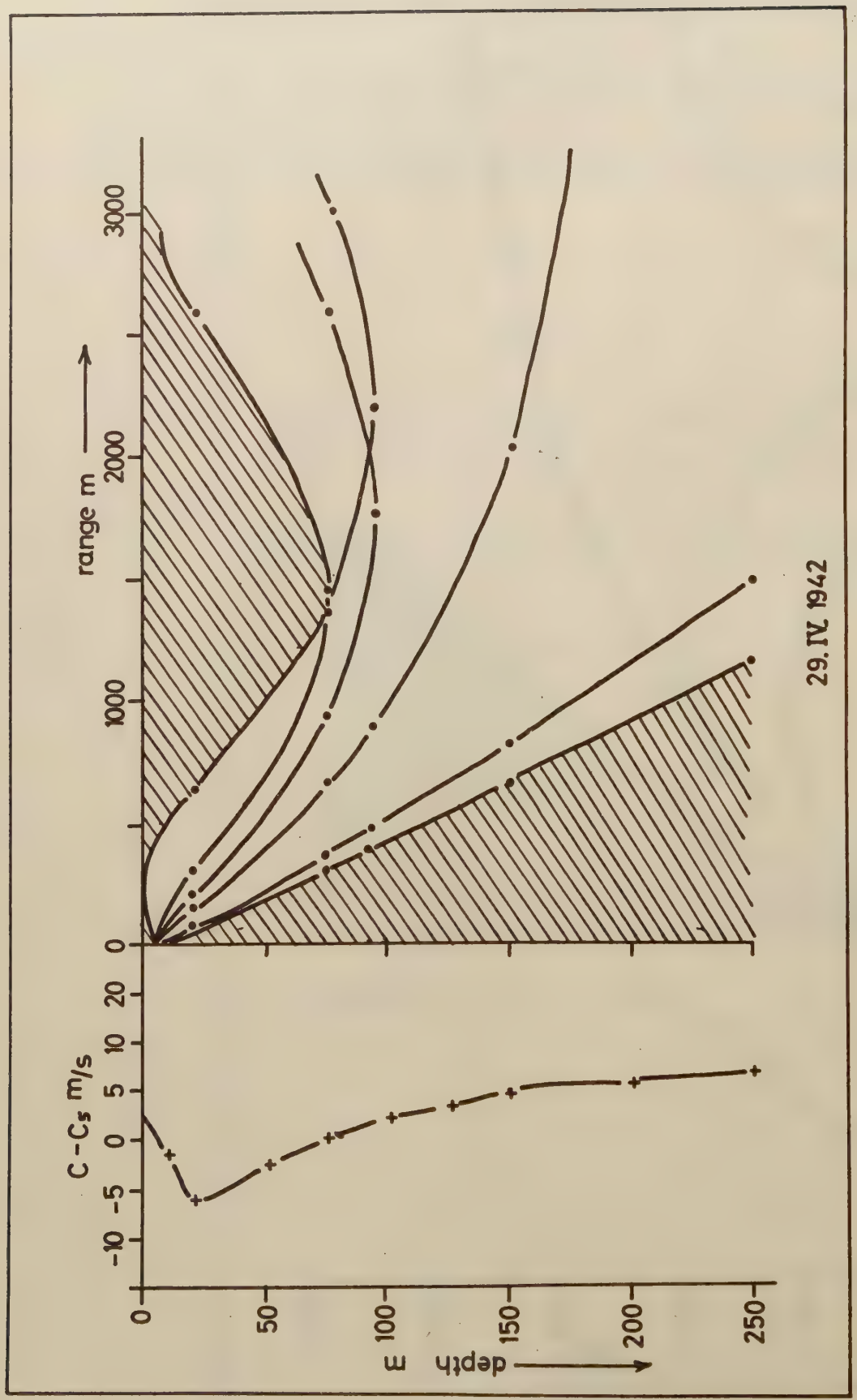
1000
2000
3000
C - Cs m/s
0
5
10
15
20
25
depth m
0
50
100
150
200
250
20. II. 1942

Figure 1A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C - Cs m/s
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-5
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depth m
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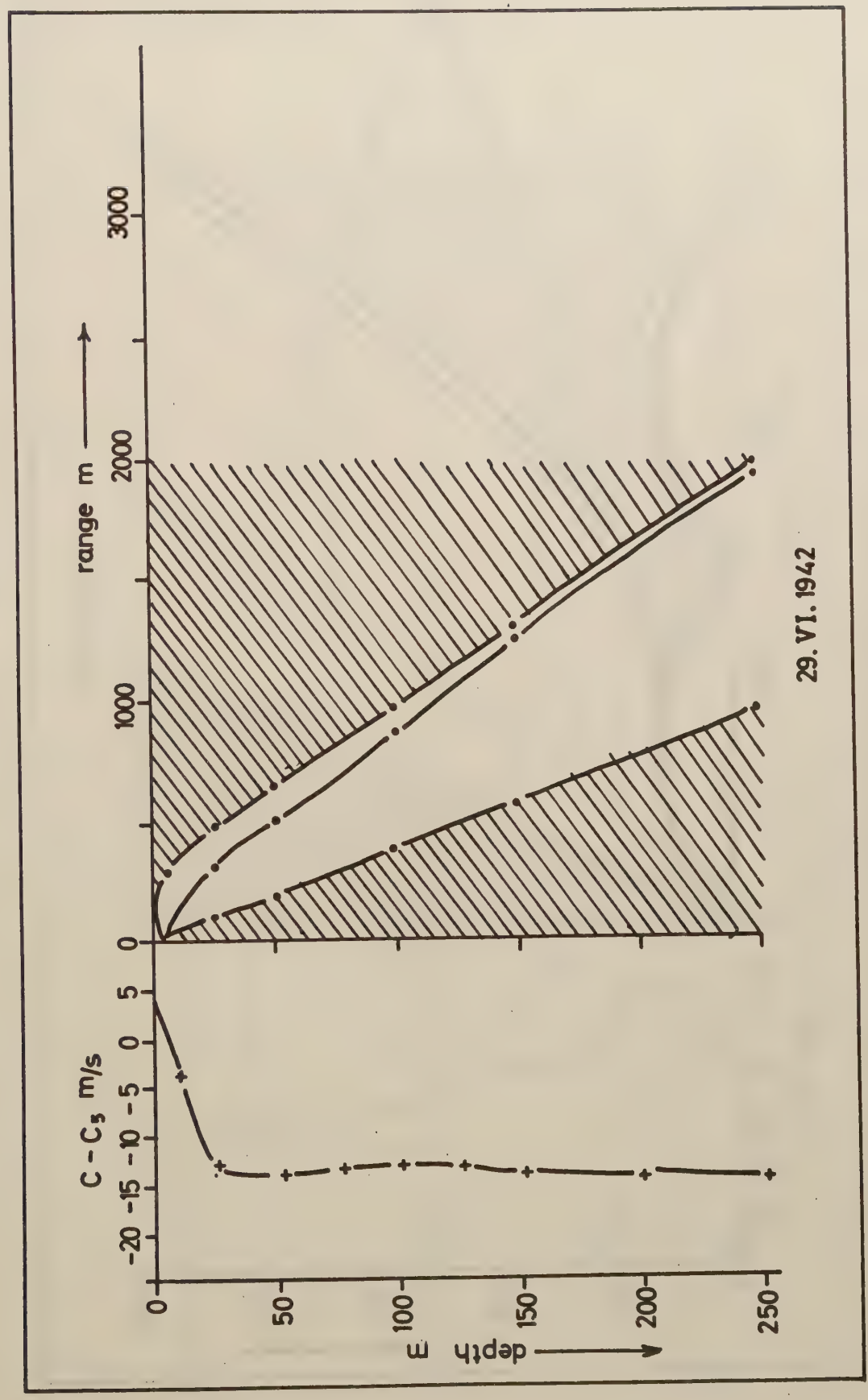
29. IV. 1942

Figure 1B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1000
2000
3000
C - C₅ m/s
-20
-15
-10
-5
0
5
depth m
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50
100
150
200
250
29. VI. 1942

Figure 1C

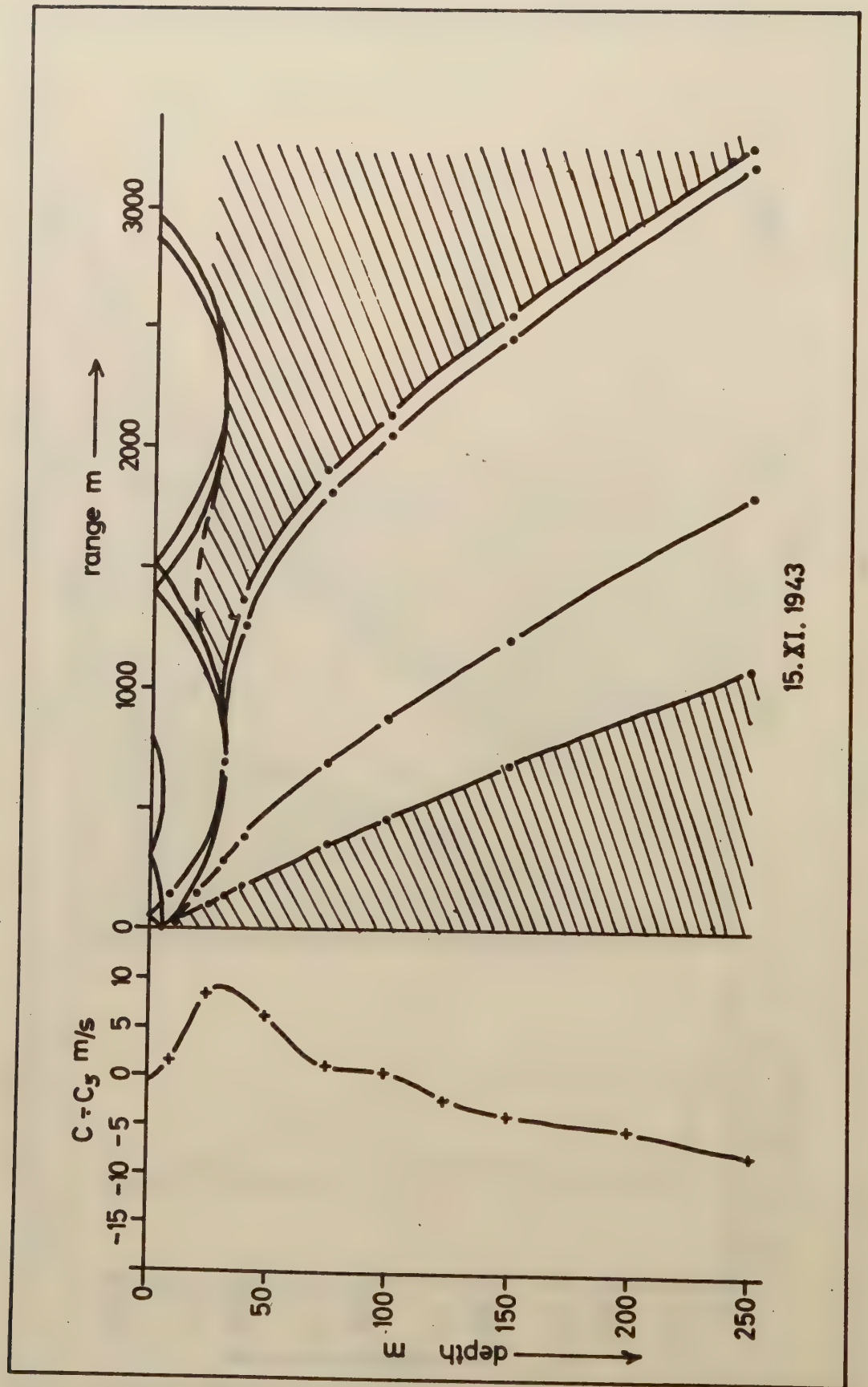
range m
0
1000
2000
3000
15. XI. 1943
C-C$_S$ m/s
-15
-10
-5
0
5
10
depth m
0
50
100
150
200
250

Figure 1D

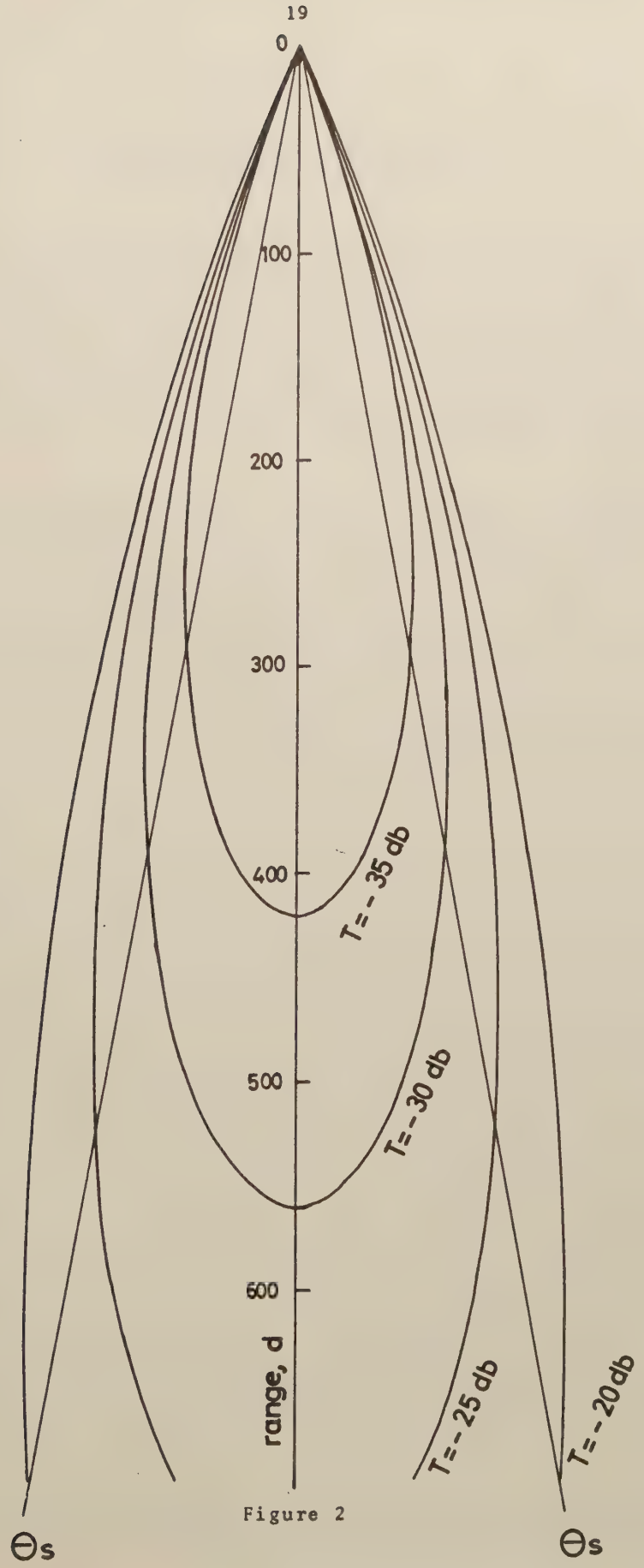

Figure 2

APPENDIX II

IDENTIFICATION OF ECHO RECORDS

The problem of distinguishing the echoes obtained from a particular species of fish from others is clearly of major importance in governing the accuracy with which estimates of abundance can be obtained by this method. Other sources of echoes include (i) marine organisms; (ii) the sea bed; and (iii) extraneous electrical and mechanical "noise" derived from various sources. With a good quality, well-maintained echo sounder, used by skilled operators the first two are the most important and largely govern the applicability of the method for accurate abundance estimation. The difficulties they create vary between localities and times, according to the distribution and behaviour of the fish stock under investigation, the composition of the biological communities in the area and the characteristics of the echo sounder in use.

The most amenable situation is one in which the species under investigation is a pelagic shoaling one living wholly away from the sea bed, whose distribution and behaviour does not change markedly in space and time and which is the only abundant pelagic fish species in the area. Although seldom met completely, such conditions are approached, for example, by the Atlanto-Scandian herring during its summer feeding and over wintering distribution in the Norwegian Sea, the Pacific sardine and Anchoveta stocks and the oceanic tuna stocks, at least in some areas. In these situations, the problem is usually one of distinguishing the echoes from those of usually much smaller, plankton organisms, the distribution of which is usually more continuous, giving rise to "layer" type traces and their individual target strengths are much smaller. Therefore, they can usually be distinguished by their echo patterns of distribution, and by manipulation of the gain on the equipment. Further distinction may be possible by the choice of transmission frequency, best suited for maximum response from the sizes of the species of fish under investigation.

In many situations, however, difficulties arise because two or more pelagic species, having similar distributional and behaviour characteristics, occur in the same area, and these characteristics change in space and time. An example of such a situation occurs in the North Sea, where, in some localities and at some times, pelagic concentrations of a number of species (e.g. herring, pilchard, sprat, sandeel, mackerel and some gadoid species) may be encountered together, and the characteristics of their individual echo record patterns vary widely. It is well known, for example, that widely different types of echo traces are given by North Sea herring at different times and places, ranging from "plumes" produced by closely packed shoals, to diffuse, layer traces, produced by more scattered, less densely packed concentrations. However, even in these situations, some degree of specific identification is often possible from careful long-term studies of echo records in the light of knowledge of the biology of the different fish species and the distribution and characteristics of the fisheries for them (e.g. Cushing (1952) for herring in the southern North Sea; Parrish and Craig (1951) for herring in the northern North Sea in summer; and Cushing (1957) for pilchard in the English Channel). Thus, in general the pattern of echo traces usually produced by adult herring and sprats in daylight with a standard, relatively low-resolution, echo sounder, operating at a transmission frequency in the range 10-50 kc/s, is mostly distinguishable by their shape and size (e.g. as "plumes" and "comets" respectively), which reflects difference in their detailed shoaling habits, etc. Further, even in areas where pelagic species mix and the distribution and behaviour of each of them changes, there are usually seasons and localities during the year when one is in substantially greater abundance than the others and the commercial fisheries are mostly based on it. Such is the case, for example, for the North Sea herring during the feeding and spawning seasons, especially the latter, when the fish are mostly densely concentrated in well-defined areas. In these localities, at these times, relatively small errors are likely to be experienced in abundance estimation, by treating all echo records as being derived from herring.

Again, as in distinguishing between echoes derived from fish and the smaller plankton organisms, some degree of distinction can sometimes be obtained by the correct choice of transmission frequency, especially if the sizes of the different

species of fish and hence their target strengths are substantially different (as, for example, is the case for adult herring and sprats). Cushing and Richardson (1955) showed that the ratios of the amplitudes of received signals from fish of different sizes at the same distance from the oscillators of a triple frequency echo sounder, working at 10, 14 or 30 kc/s, differ significantly, and that over this range, the amplitudes increase with frequency with decrease in size of fish and vice-versa. Therefore, given the range of sizes of the species under investigation (from catch sampling in the survey area), they conclude that identification may be possible, with the use of a range of frequencies.

In addition to these methods, some degree of identification of the source of echoes can be obtained by catch sampling with appropriate fishing gear at the depth of the echo records. For example, this has been used by many workers in investigating the sound scatterers comprising the deep scattering layer and other layer type traces (Dragesund and Olsen (1965)). More direct observational techniques can also be used such as underwater photography (Craig and Priestley (1963), Blaxter and Parrish (1958), Truskanov and Scherbino (1964)); television (Barnes (1958)); and visual observation from underwater vehicles (Zaitsev and Azhazha (1959)). In some circumstances explosive charges, detonated at the depth of the echo traces, can also be used for identification (e.g. Blaxter and Parrish (1958)).

Thus, for pelagic species, the problem of identifying the echoes produced by the species under investigation can usually be solved satisfactorily, by careful studies of echo records in conjunction with catch sampling and other techniques. However, greater difficulties arise in identifying the echoes of demersal species, living on or close to the sea bed. The principal problems for such species are in distinguishing (i) fish from sea bed echoes, particularly on rough ground; (ii) the echoes from the particular fish species under investigation from those of other species.

The first of these problems concerns the resolving power of the equipment (see Appendix I). Much depends, of course, on the actual density and packing of the fish on the sea bed. In practice, if the fish are distributed singly, or in small groups, 1-2 metres or less from the sea bed, as is probably the case with many flatfish species and some roundfish ones in some localities and times, the distinction between fish and sea bed echoes cannot often be made with confidence with such echo sounders. However, this represents the limiting case, and for many demersal species, which are exploited by bottom fishing gears, their aggregation and packing properties are such that distinctive traces of at least the main concentrations can usually be clearly recognized with such sounders close to the sea bed. This is illustrated by English investigations in the Barents Sea (Ellis (1956), Richardson et al. (1959)), and their recognition has been greatly facilitated by the introduction of improved display equipment such as the "white-line" system in paper recorders (Saetersdal, Vestnes and Midttun (1957)) and the PPI display system, either alone or in conjunction with a paper recorder.

Attention has also been paid by echo sounder manufacturers in recent years to the development of higher resolution equipment using higher transmission frequencies, giving shorter pulse lengths, and much narrower beam widths, aimed at improving the discrimination of fish traces close to the sea bed. Their importance will be discussed further under echo counting.

In addition to the above difficulties, the discrimination between the echoes of different species within the demersal fish concentrations is often more difficult than for pelagic ones. This is mainly because larger numbers of species with similar sizes of individuals and target strengths are often found together in this zone and they are similarly distributed so that they tend to give less specific echo patterns than the pelagic species. Again, however, as with the pelagic species, information on the species present can be obtained by sampling with trawls and other bottom fishing gears in the survey area (either by a commercial fishery or by research vessel). This will indicate the number of species present, and provide some guide as to their relative proportions (assuming that there is not a large differential selectivity by the gear). Photography and direct underwater observation can also be used in some circumstances. Further, if there are major differences in size between the species giving rise to the echo records, it may be possible to improve the distinction between them as well as increasing the general resolution by choice of transmission frequency.

APPENDIX III

ECHO COUNTING

(This subject is discussed from the physical point of view in Appendix I)

There are various levels of sophistication in echo counting, but all instruments used must be calibrated. There is a second requirement which is less obvious. It is that the zone in which counting is done should be limited to the capacity for indentification. There are physical means of sizing fish targets available, but this is not identification; such methods are best used within a given range of identification.

Ideally, echo counting for population analysis should be used in the first place where all the population is present, as for example, on a spawning ground. Then the counts can be checked by other methods, as for example by measuring egg production and the problem of identification is simpler because the spawning fish are likely to provide the most abundant targets on their spawning ground. Given counts on the spawning ground, counts elsewhere in the species range can be used for availability studies - which may be of great importance in unfished areas.

(a) Presence and absence recording

The simplest form of echo counting is that based on the presence or absence of echoes from fish in any transmission. An echo from fish can be taken as one which occurs more than once at the same range in successive transmissions. This convention can be used to distinguish fish signals from noise. It is unlikely that "noise coincidences" comprise more than a very small proportion of the true fish echoes. Another convention is that the amplifier gain is turned high enough to mark noise on the paper record and then back again until the paper record is clean. This technique ensures that the signal-to-noise ratio is maintained at a high enough level under a range of varying noise conditions. Each signal from fish must be then much higher than the noise Because the change in noise throughout a cruise is not likely to be very great (less than the actual signal-to-noise ratio), the estimates of presence or absence of fish signals within a given transmission are good ones.

Although the prime estimate is one of presence or absence within a transmission, the data can be treated quantitatively. In English investigations, the echo traces of pelagic fish are estimated in width (i.e. in successive transmissions) at the widest point of the fish trace (Cushing (1952)). The records can be charted as mm of trace per 10 miles steamed. Here it is assumed that there are no changes in vertical extent of the trace. If a form of grid survey has been used, areas of relative density can be charted quantitatively. When such methods were combined with pilchard egg surveys, it was possible to estimate the numbers of pilchards in an average trace (Cushing (1957)). Normally, however, the method will only indicate that one area is richer than another, relative richness being correctly given, variations in fish density being assumed constant. But no absolute quantity of fish is given with this technique unless catches between two areas have been correlated with quantities of echo trace.

(b) Counting individuals

In contrast to the estimation of relative abundance provided by the method of presence and absence recording, an estimate of absolute abundance is given when single fish are recorded. Figure 3 (A and B) shows records of single cod and single herring. Hylen, Midttun and Saetersdal (1961) made echo surveys of cod in the Barents Sea based on counts of single fish in midwater. Since that date surveys of single whiting, single sprats and single herring have been made with high frequency equipment in the North Sea by the Marine Laboratory in Aberdeen and the Fisheries Laboratory, Lowestoft. Typical records using this equipment are given in Cushing (1963).

(c) Estimation of target strength

As shown in Appendix I, an essential requirement is the measurement of target strength of fish i.e. the absolute signal received from a fish under given standard conditions. Measurements have been made on perch, herring, cod, coalfish and tuna. A reasonable law for the relation of target strength to size of fish has been

estimated (Cushing (1964)). Hence it is possible to convert voltages as at 1 m from the transducer to estimates of fish numbers, if they have been identified and roughly sized. The most important point to remember is that the average signal from fish comes not from the axis but from a point somewhere near the median of the directivity distribution between axis and first minimum. So the signals as at 1 m from the transducer should be corrected by this directivity factor.

(d) Individuals and multiple echoes

If there are many fish in a range slice sampled by a pulse, then the echoes from the fish will either add up or cancel out and the voltage is proportional to the square of the numbers. This generalization can be used so long as the number of individual fish echoes recorded in the range slice is very small compared with the number of multiple echoes. As echo sounders have developed, their discriminating power has increased and so the chance of recording echoes from individuals has increased. For example, a high frequency sounder can have a very narrow beam and a pulse length of perhaps 70μ sec. With such an echo sounder most of the echoes from herring received at night on the spawning ground are from individuals.

However, the distinction between individual and multiple echoes must always be variable. Echoes which are all individuals at night may become multiples in the daytime due, for example, to shoaling. On a paper record, an individual fish can easily be recognized as a "fingernail" trace. Any automatic counting system must make the same recognition, because we must count $\Sigma(a + \sqrt{b})$ and not $\Sigma(\sqrt{a + b})$, where a is the echo from an individual and b is that from multiples. Mr. B.R. Carpenter of the Lowestoft Laboratory has solved this problem in categorizing echoes from individual fish as comprising a fixed and minimal number of cycles (Carpenter (1966)) which can be counted. So, given a target strength for herring, for example, the fish might be counted on their spawning grounds, by day and by night.

An alternative to the above is to lengthen the pulse length or widen the beam so that no individual signals are recorded. Then all voltages are integrated within set depth ranges. The number of fish may be given from the square root of the voltage, if the target strength is known. This pre-supposes that the fish is not many times larger than the wavelength of the sound used and that the sound reaches all fish in the shoal equally (Dragesund and Olsen (1965)). If these two conditions are not satisfied, the relationship between the number of fish and the voltage may be a complex one. The empirical square root relation is useful for some purposes, (Richardson et al. (1959), Scherbino and Truskanov (1966)) but it is preferable to break the multiple targets into individuals if possible.

The systems described depend upon independent identification and upon the mean target strength being allotted for a given size of fish. In some populations there is a considerable size range, and hence range in target strength. Because an echo sounder cannot distinguish in multiples between a large number of small targets and a small number of large targets, variance in size is transformed to variance in numbers.

If all echoes were of individuals, a voltage can be allotted to each individual fish. The distribution of such voltages has two components of variance, that in target strength and that in directivity. Under some restrictive circumstances the two components of variance are independent and so, given the observed distribution and and the directivity distribution, the distribution of target strength can be deduced. In other words the population could be sized with an echo sounder. However, under other circumstances, the distribution of directivity and that of target strength are related, the bigger the target, the further out will it be recorded (see Figure 2 of Appendix I). The restricted condition is the shallow water one, where the cut off to the beam in angle is sharp.

The difficulties described in the last paragraph are due to the directivity distribution. This distribution disappears if a sector scanner or CTFM (continuous transmission, frequency modulated) sonar is used. Without describing either system, a signal has the same value at whatever bearing it is recorded. Hence the distribution is one of target strength only. So a size distribution is being recorded, so long as the signals can be treated as being from individuals, which is probably the case at fairly close ranges.

(e) Methods of size discrimination other than target strength

It is possible that size discrimination can be done independently of target strength. There are at least two methods that can be used. If one frequencyis put in the zone of Rayleigh scattering and another in that of geometric reflection, then the ratio of signals at the two frequencies is an index of the size of the fish (Cushing (1964)). A distribution of these ratios will emerge. As fish sizes are roughly distributed between the zone of Rayleigh scattering and that of geometric reflection, this technique can be readily exploited.

The second technique depends on the "Thumper". This machine transmits lower frequency sound [100-2000c/s] and the air bladders of fish resonate to it and a beat is reported on the echo traces. From the beat and the depth of the fish trace, an estimate of the size of fish can be made. In principle this could be an accurate method, so long as the fish are always at the same distance from each other (McCartney (1966)).

Summarizing, there are three forms of echo counting :

(i) presence or absence of signal from fish within a transmission;

(ii) summing of signals received from fish, either in an integrated form, or as individuals;

(iii) counting and sizing of fish, by target strengths, using sector scanners or CTFM sonars.

The first method gives relative measures of abundance between areas. The second gives absolute measures of abundance with rather a high variance due to instrumental difficulties. The third will give absolute measures of abundance with least variance.

Figures

Figure 3A : A record of a layer of herring made on the Egersund Bank (24 September 1965) with the Lowestoft 100 kc/s echo sounder. Each trace is a record from a single herring.

Figure 3B : Recordings of single fish, mainly cod of length 35-40 cm, made with a Simrad EH sounder during a trawl haul on the east coast of Finnmark (9 May 1966).

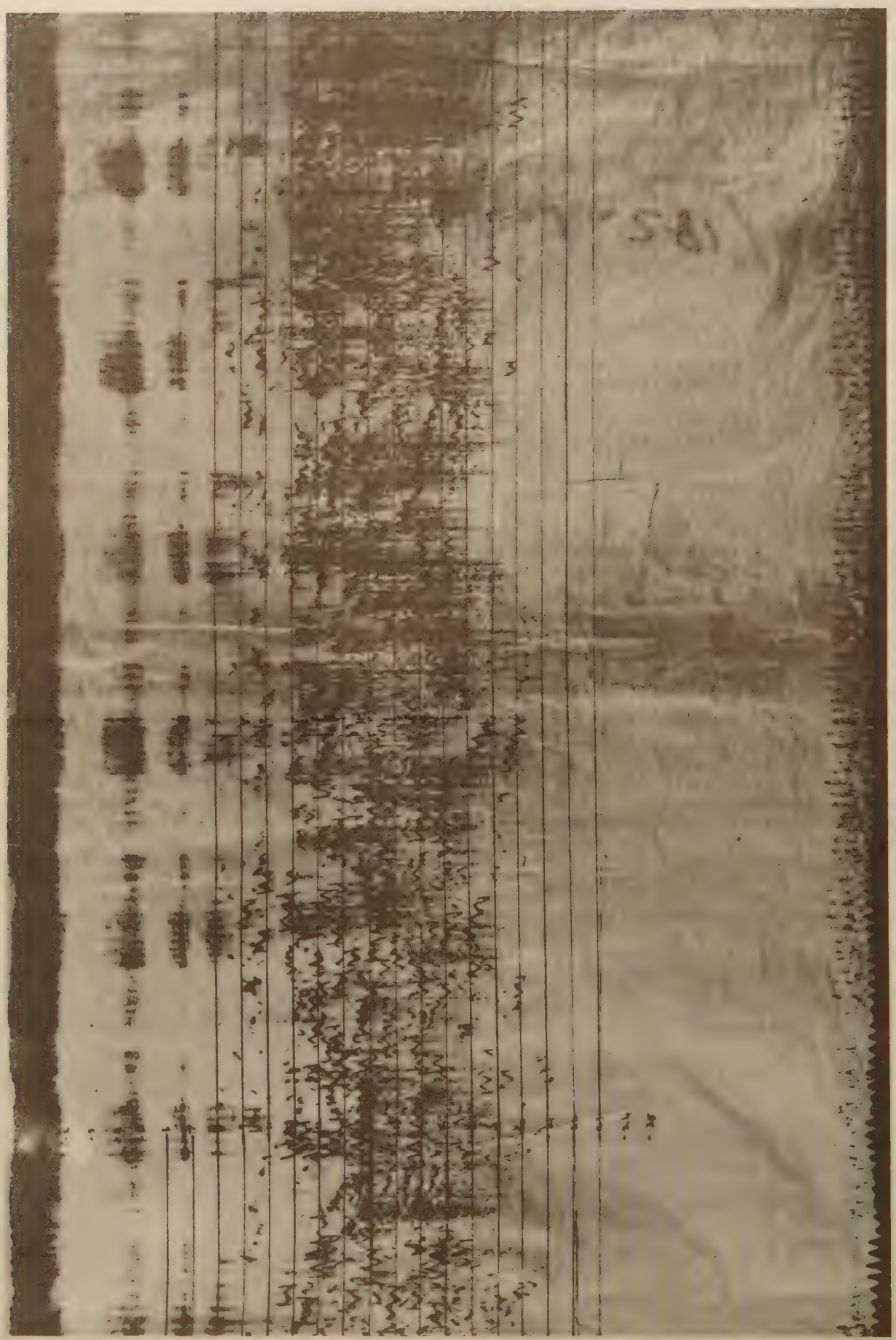

Figure 3A

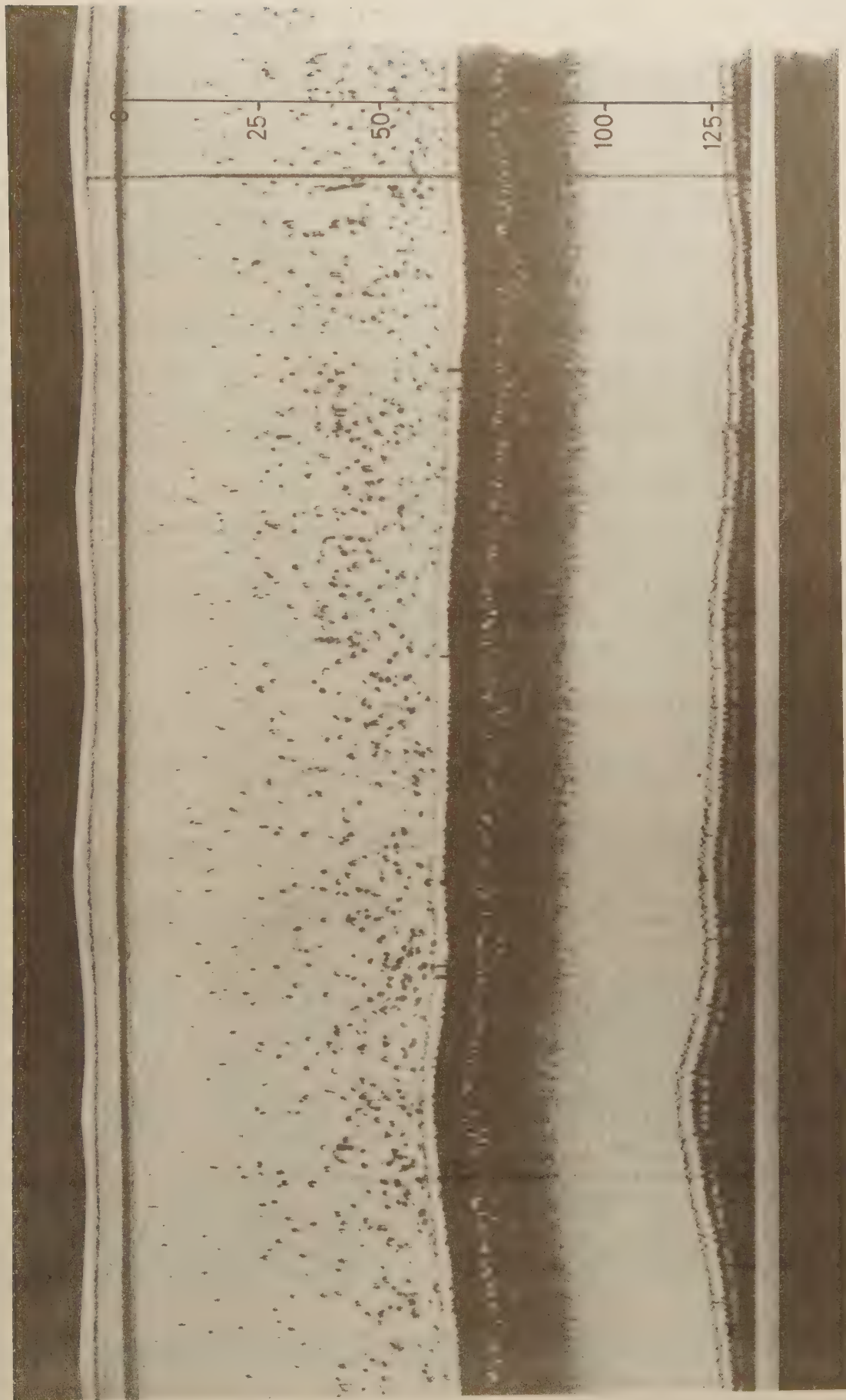

Figure 3B

APPENDIX IV

OPTICAL METHODS

In recent years much attention has been paid to the development of techniques for observing fish directly, other than by acoustic means. These are :

(1) Underwater Photography and Television by self-contained or remotely controlled cameras, operated from surface vessels

(2) Direct Visual Observation and Photography by free swimming divers, in shallow water and from underwater vehicles at greater depth.

While, for the most part, these techniques have been developed for, and applied in, investigations other than of abundance estimation, they have been used for this purpose in some situations, especially in conjunction with other methods. In addition they may be used in some situations to calibrate a sampling gear, especially for benthic organisms (e.g. Czihak (1959)).

(1) Photography and television by self-contained or remotely controlled cameras

The obvious advantages inherent in the use of this self-contained or remotely controlled equipment are that the identification of the organisms present within the field of view of the camera is usually possible, and provided a target of known size and distance from the lens is photographed, direct measures of their size and density (by numbers) can be made at each sampling point. However, they also suffer a number of serious deficiencies compared with acoustic detection methods which limit their applicability for general quantitative survey work. The main disadvantages are :

(a) their fields of view are very small compared with acoustic detection equipment

(b) except in shallow clear water in daylight, artificial light sources are required, which may, if continuous, affect the distribution and behaviour of the organisms

(c) their usefulness is very dependent on the light scattering properties of the water mass

(d) they are relatively delicate equipment (especially television) which cannot readily be used to give continuous records under survey conditions.

For these reasons, the main use of this apparatus in abundance estimation of fish and other active organisms in the open sea is likely to continue to be in supplying "spot" information on the identity and density (as numbers per unit volume or area) of organisms in concentrations recorded by other methods, especially acoustic ones. The use of still cameras for this purpose has been made in investigations of the size of the Atlanto-Scandian herring stock by Russian workers (Federov, Truskanov and Yudanov (1964)). Acoustic surveys were made of the over-wintering concentrations of this stock in the Norwegian Sea, and the total volume of fish was estimated from the records obtained. An automatic "still" camera, with electronic flash, was lowered into echo traces of different size and the density (numbers per unit volume) of fish within them was estimated from the photographs. Estimates of total abundance, obtained from these data, agreed remarkably well with independent estimates obtained by Norwegian and Icelandic workers from tag recapture data. Still cameras, with electronic flash, have also been used by Scottish workers (Craig and Priestley (1960)) for estimating the density of herring on a spawning bed, and similar methods have been applied by Norwegian workers to identify fish in echo traces in the Barents Sea (Midttun and Saetersdal (1959)).

While the application of these techniques is likely to be confined to density estimation in conjunction with acoustic detection methods for free swimming organisms,

they have a more direct application by themselves in abundance estimation or some sedentary benthic organisms (e.g. shellfish species) which cannot normally be detected by acoustic methods. For such organisms the method of estimation consists of making observations at points over the survey area by either photography or television at a known distance from the sea bed, so that the area sampled at each point is known, and counting the number of organisms on each exposure or on the viewing screen. These methods provide direct measures of the density (per unit area of sea bed) at each point, from which average density over the whole area can be calculated and total abundance can be estimated by contouring and aggregating over the whole area surveyed. The published literature contains examples of the use of both photography and television in these studies (e.g. Posgay (1958), Czihak (1959), Czihak and Zei (1959), Craig and Priestley (1963) - for photography, and Barnes (1958, 1959) - for television) but of the two, photography has the following advantages :

(i) the equipment is cheaper and less delicate

(ii) the ease and rate of handling of the cameras aboard ship is greater, especially with self-contained remote controlled "still" cameras with electronic flash

(iii) the "still" camera with electronic flash does not require continuous sources of light, and so is less likely to affect the distribution and behaviour of the organisms

(iv) photography produces permanent records which can be subsequently analysed in detail: if necessary, stereophotography can be used to assist in the identification of the organisms.

Under good conditions of water clarity and for inactive, non-burrowing, benthic organisms which can be easily identified, this method is potentially a very accurate one, since absolute counts of the number of organisms can be made at each sampling point. However, the accuracy of abundance estimates obtained with these methods will be governed by the distribution and habits of the organisms. It will be greatest for sessile forms which are always exposed to the camera's field of view, but it will be less for active, swimming or burrowing organisms or those which seek concealment in crevices or rocks. For such organisms under-estimates of their abundance and density are likely to be obtained. Knowledge of these habits, especially of their diurnal changes, will often assist in minimising these errors of estimate by allowing a choice of survey to be made at the times when the organisms are exposed to view on the sea bed.

The efficiency of surveys with self-contained, automatic, "still" cameras may be greatly increased with the use of towed or self-contained carriers, the depth and course of which can be controlled remotely.

(2) Direct visual observation and photography by divers and by underwater vehicles

The use of direct visual and photographic observation by free swimming, aqua-lung divers in shallow water has increased greatly in recent years in many research projects, including abundance estimation. In the main, the conditions governing the applicability of this method in such studies are similar to those of the photographic and television methods outlined above, but the diver has the advantage of greater mobility, especially if equipped with a towed or self-propelled "sledge" or other shallow water vehicle, which increases his area of observation. As with the above methods, the easiest situation for accurate quantitative studies arises with the larger sedentary benthic organisms of which the divers can make census counts within defined areas, and, in addition, censuses and density estimations can also be made of free swimming organisms more readily than is possible with cameras worked from a surface ship.

However, this technique is subject to a number of important limitations, which restrict its usefulness. For example, free swimming divers can only operate in relatively shallow water - up to 100-200 feet, they cannot work effectively for general survey purposes in the dark, and their submersion times are limited (this varies with depth, water temperature, and air supply, but 30-50 minutes is the limit for the 'average' aqua-lung diver).

Therefore much attention has also been paid to the development of self-contained, manned, underwater vehicles, equipped with facilities for direct visual and photo-

graphic observations. Many types of such vehicles have been developed or are currently under development, which fall into the following broad categories :

(a) underwater chambers, or vehicles, lowered and hauled by cable from a stationary surface vessel, or towed by a moving one

(b) independent (during submersion) underwater chambers or vehicles but with very limited self-propulsion range and so dependent on parent surface vessel

(c) completely independent, underwater vehicles with relatively large self-propulsion range (submarines).

Of these, the category of vehicles most suitable for open sea abundance estimation work is probably the latter, since such vehicles can constitute completely self-contained, independent, survey vessels, covering large areas. In many respects, a submarine equipped with acoustic fish detection devices (sonar and echo sounders), observation windows, cameras, search lights, and closed-circuit television, perhaps constitutes the best possible platform for combining the acoustic and direct observation methods in extensive surveys, especially of pelagic fish concentrations, in depths up to at least 200-300 m. As yet, the only extensive application of such a vehicle in open sea fisheries investigations has been by Russian workers (Zaitsev (1959), Zaitsev and Azhazha (1959)), and their published results, although far from comprehensive, show clearly its potentialities for abundance estimation.

APPENDIX V

AERIAL SURVEYS

The operational advantages of aircraft, as against surface craft, as platforms from which to observe fish and oceanic phenomena, derive from :

(1) the greater altitude at which they can place the observer, giving greater range of observations and some viewing into the water;

(2) the greater speed at which they can travel, giving a greater length of viewing transect per unit time.

The degree of advantage of aerial surveys differs from aircraft to aircraft, and depends upon what has to be observed and the conditions under which the observations have to be made.

The advantage of a greater area searched by aerial survey must be weighed in each situation against the value of sustained and closer observation of a small area from a surface craft; a judgment in this matter will take into consideration the behaviour (more especially the periodicity of appearance) of whatever is to be observed, and the dimensions of the area over which observations have to be made. As an illustration of the problem we cite two extreme cases :

(i) where observation has to be made at a fixed site of a phenomenon of unknown periodicity;

(ii) where observation has to be made in a large and ill-defined area, of instances of a phenomenon whose distribution within the area and pattern of appearance (in time) are unknown.

In the first case a stationary observer is needed whereas in the second case a moving observer is needed. But, whether in the second case an aerial observer would have special advantage over an observer in a boat would depend on whether the boat could survey the entire area before some significant change had taken place. In general, aerial surveys are especially valuable for the following purposes :

(a) to make a preliminary reconnaissance of an unexplored area which is of such size that conduct of such a survey by surface craft would either require a large number of craft or occupy a considerable time

(b) to provide a synoptic picture of phenomena in an area of dimensions greater than the area coverable by surface craft within the period that the phenomenon is present

(c) to locate a phenomenon (for example, fish schooling and development of temperature fronts) appearing intermittently and scattered over a large area and to direct surface craft to the phenomenon.

In these situations aerial surveying can contribute importantly to work aimed at estimating the abundance of fish. In some special cases, of species which school at or just below the surface, an aerial observer can make quite reliable counts of the schools and estimates of the average number or weight of fish in the schools and these data can permit a tentative estimate of size of stock engaged in the schooling behaviour at the time of observation. The value of the estimate will be greatly influenced by the state of knowledge as to distribution of the species and as to participation by different sections of the stock in the schooling behaviour. Thus, even in these special cases, aerial surveying is not self-sufficient and in most cases the contribution of aerial surveying is to assist and complement the work of surface craft, which it does, as indicated above ((a), (b) and (c)), by delimiting areas of search, by providing synoptic pictures and by directing the movement of

surface craft and supplementing their observations. In this sense it should be noted that the observations by spotters in aircraft operated by industry can furnish a lot of valuable data: of themselves these data carry some of the limitations of fishing-boat catch and effort data, but combining them with data from an aircraft engaged on survey adds greatly to their value.

Aircraft have been used in survey work in many countries. They have been used in Peru and Chile for the anchoveta and whale fisheries; in the USA for tuna, sardine, shark and menhaden fisheries; in the USSR and Iceland for herring fisheries; in Australia for tuna, Australian salmon, clupeoid and whale fisheries; in Canada, and in Japan. In some cases this work has consisted of making an exploratory reconnaissance of an unexploited area, in others of furnishing data to supplement the results of surface craft in a study of exploited stocks.

Operational aspects

The strategy and tactics of any survey are determined by the place to which it can be assigned in a two-way classification relating to (1) the phenomena to be observed (fish or oceanic feature or some combination of these), and (2) the intended character of the survey, that is, whether it should give coverage of as large an area as possible (e.g. a prospecting survey intended to achieve a broad characterization of an area) or should seek to maximise the density of observation.

Under the heading strategy we include determination of the area to be surveyed and the season of survey, assessment of what is already known of the area, choice of track along which the aircraft would travel, frequency of flights, choice of equipment. Under tactics we include speed and altitude of operation, co-ordination of aerial operations with surface operations especially in connection with identification of observed phenomena, choice of flying times. Hynd (1964) has given formulae for estimating the number of aircraft required under various conditions for surveys of areas of various dimensions. His paper also discusses the relative efficiency, in searching, of surface craft and aircraft.

Equipment

No specifications have been laid down in the literature as to the characteristics required in an aircraft to be used for aerial survey: search work has been done from a wide variety of aircraft. In principal a spotting aircraft should offer good unimpeded observing positions, be capable of flying at relatively low levels, at low speeds, over extensive sea areas relatively far to sea, whilst meeting all standard civil aviation safety requirements. In general these requirements mean a small two-engined aircraft capable of carrying, say, four people. The wings of the aircraft should be so placed that they do not impede observation. The flying level required depends in part on visibility, on sea-surface conditions, and on the characteristics of the fish or other things being sought. For fish-spotting, 600 to 800 feet is thought by many observers to be the appropriate height, but the deeper that the fish swim, the higher must be the flight level. The required flying speed is also determined by the considerations of visibility, etc., but most observers believe that observing cannot be efficient at speeds greater than 110 knots. The endurance required in an aircraft for survey work is determined by the flight plan proposed but of course in practice compromise has often to be made between desirable flight plan and endurance of available craft. The capabilities of pilot and observer in such work as this may also impose limits on flight plans and hence relax the endurance requirements. The choice of aircraft for a survey may also be influenced by the need to provide accommodation for special equipment (such as radiation thermometer): such a requirement may affect the endurance calculations, or the demand for space in the aircraft.

Whatever aircraft may be chosen for a survey, it is essential that it should carry not only the normal navigational and radio equipment but also have means of direct communication with accompanying surface craft: if possible it should have special navigational equipment to permit precise determination of the positions at which particular phenomena are observed. As means of communication, beacons and marker dyes have been used in addition to radio.

So far we have considered aircraft solely as means of carrying observers but they can be used to carry also special equipment. For example radiation thermometers

can be used for the detection of surface temperature discontinuities and for the development of synoptic pictures of temperature distribution in the survey area. Cameras can be carried as a means of extending, deepening and recording permanently, the observations made. Sonar buoys can be dropped from aircraft and data recorded from them.

The foregoing notes relate essentially to the use of conventional propeller aircraft operating at relatively low altitudes and speeds, from land bases. This is chiefly because the cost of operating such aircraft lies within the range of vessel costs and in some instances represents an economy against surface craft operations. However, other types of aircraft have been used and still others could be brought into use for these purposes. Float planes have been used and presumably sea planes and amphibians could be used. The use of helicopters has been attempted although there is no published account of extensive use of them. Under certain circumstances helicopters could give considerable advantages: they could be used where it was desirable to remain for extended periods at height over a chosen area and to be able to move off quickly to survey some wider area. Helicopters could be used as platforms from which to lower a wide range of oceanographic equipment. Still another possibility is that high-altitude aircraft with high-resolution photographic equipment might furnish virtually instantaneous maps of relatively large sea areas.

Technical staff

In some cases the role of pilot and observer can be combined in the one person, but even if a separate observer is available the pilot should have some training in observing and should be fully conversant with the survey programme. Observing is not a simple matter: it requires good vision and a trained ability to detect and recognize various signs. Many workers contend that proficiency in observing can be developed only after many months of experience.

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